Summary Report on Working Group 5: Electromagnetic Structure-Based Acceleration

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Abstract. Recent progress and new developments in Electromagnetic Structure-Based Acceleration were presented in this Working Group (WG). The presentations made to the WG were separated into two categories: slow-wave and fast-wave accelerating structures. The slow-wave talks included a theoretical study of accelerators at optical frequencies that showed there are important and surprising differences between optical structures and traditional microwave accelerators. Practical issues for dielectric loaded accelerators were also addressed including a novel method for frequency tuning of dielectric structures and, in a joint session with the mm-wave sources WG, dielectric high power test results were presented. Theory and simulation results were presented for both laser-driven and beam-driven (i.e., wakefield) novel structures including cylindrical and planar dielectric devices and photonic band gap (PBG) devices including a scheme to mimic a plasma channel with a PBG. In the fast-wave talks, progress in developing highly-tapered inverse free electron lasers (IFEL), staging IFELs for monoenergetic laser acceleration, and generating attosecond electron pulses were presented. New designs and applications of cyclotron-based devices driven by laser or RF energy were also discussed.

INTRODUCTION

The electromagnetic field configuration appropriate for acceleration in a structure-based accelerator is determined by a structure external to the region of interaction between the beam and the accelerating field. This is opposed to plasma-based accelerators in which the plasma at the location of the beam provides the accelerating medium. In keeping with the tradition of this working group, the structure-based class of advanced acceleration schemes was broadly defined to include externally powered devices that span the electromagnetic spectrum from microwave to optical as well as wakefield structures powered by beams.

Structure-based acceleration methods are conveniently classified by phase velocity into either slow-wave or fast-wave. Slow-wave schemes are further subdivided to include wakefield accelerators (e.g., dielectric wakefield accelerators), externally powered, non-metallic devices (e.g., dielectric loaded accelerator), accelerators driven at high frequency (e.g., laser driven) and novel metallic structures (e.g., photonic band gap accelerators).

Fast-wave schemes essentially imply the phase velocity of electromagnetic wave is traveling at or greater than c. Thus, schemes must be employed to allow the electrons to remain phase matched with the light wave. For example, in inverse free electron lasers

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(IFEL), the magnet array (wiggler/undulator) causes the electrons to travel in an oscillatory path. This means the electrons take a longer path length than the light wave propagating straight through the undulator. Thus, the electrons slip in phase with respect to the light wave because of both phase velocity mismatch and path length differences. Therefore, to maintain constant phase synchronization, the phase slippage with each oscillation is designed so that the electrons intersect a subsequent light wave at the same phase point as the previous light wave the electrons were riding on. This is fundamentally different than schemes, such as inverse Cerenkov acceleration, where the electrons remain phase matched with the same light wave throughout the interaction region.

The following sections have been arranged to make it easy for the reader to quickly find the area of research aligned with his/her interests.

SLOW-WAVE ACCELERATORS

In this section we summarize the presentations made during the slow-wave accelerator sessions. These talks addressed both general considerations common to all slow-wave schemes as well as recent developments of particular slow-wave schemes.

Fundamental Considerations

Given the growing trend towards high frequency accelerating structures, L. Schachter of Technion – Israel Institute of Technology discussed what differences one might encounter when trying to scale an accelerator from the microwave to the optical band. He began by pointing out that optical accelerators will be made of a dielectric material due its superior high electric field and low power loss characteristics over metal. Operating at the maximum accelerating gradient that the dielectric structure can support (this material damage limit is quantified by the maximum fluence), one can then calculate the optimal charge to be accelerated as determined by the desire to maximize the overall efficiency. Another interesting observation is that self-wake experienced by an electron bunch traveling through a microwave accelerator can excite 1000's of modes, but only a few modes (tens) will contribute in optical accelerators. This is because at very large frequencies (or very small wavelengths) all polarization mechanisms "die out", i.e., there is no response to the high frequency field, which means that the dielectric constant ε_r will approach 1. In terms of wavelength, the dielectric materials become transparent near $\lambda =$ 50 nm.

Unlike the mature technology of metallic-based accelerating structures, there are several fundamental issues that need to be addressed before any acceleration scheme based on dielectrics becomes a reality. A. Kanareykin of Euclid Concepts LLC and ANL presented a means for solving one of these fundamental issues, namely, a method to vary the resonant frequency of a dielectric-loaded structure. It consists of a thin layer of a ferroelectric material of high permittivity, attached to conventional dielectric of low permittivity. A DC bias voltage is used to vary the permittivity of the ferroelectric layer and thus tune the overall frequency of the accelerating structure. A design for an 11-GHz cylindrical dielectric-loaded accelerating structure, with an overall structure tuning range of (2-4)% using a BST ferroelectric-oxide compound with an adjustable permittivity of 300-500, was presented.

Externally Powered Exotic Structures

Dielectric Loaded Cylindrical Accelerators

Due to the difficulties encountered with operating metallic structures at very high electric field [1], there is a growing interest in pursuing dielectric waveguides as alternative slow-wave structures [2, 3]. If dielectric structures are demonstrated to be capable of high power operation, then there are several advantages these structures have over metallic structures. Advantages of cylindrical dielectric structures are: (1) they are easy to fabricate and potentially cheaper to make since they are simple cylinders; (2) the parasitic higher order modes (HOM) are very simple to damp [4]; (3) the dark current is less since there are no conduction band electrons; and (4) the maximum electric field in the structure is on axis, which should translate to high operating accelerating field devices. There are several issues that need to be addressed before dielectric-loaded accelerating structures can be considered practical including: (1) dielectric breakdown, (2) dielectric tuning, and (3) temperature control and stability.

J. G. Power from ANL presented the preliminary results from the first high power tests of two X-band dielectric-loaded accelerator (DLA) prototypes. The tests were conducted at the magnicon facility at NRL; see these proceedings. In the first high power test, 0.6 MW of RF power was delivered into the traveling-wave DLA prototype, which corresponds to an acceleration gradient of 3-5 MV/m and an S_{11} of about 90%. The input power was limited due to arcing in the input coupler as evidenced by an increase in vacuum near the input coupler during the test and visible damage to the input coupler as revealed by a visual inspection after the test. In the second high power test, very little power (<100 kW) was coupled into the standing-wave DLA prototype due to a power sensitive mismatch. A visual inspection of the input coupler once again revealed arcing-related damage to the dielectric in the input coupler. In neither case was there evidence of dielectric breakdown in the structure. W. Gai from ANL presented a new modular design for the above traveling-wave and standing-wave DLA structures. He predicts this design will eliminate the arcing problem in the input couplers. This modular design couples power from the TE waveguide into an all-metal TM waveguide, then through a tapered dielectric matching section, and finally into the accelerating structure. These new modular structures will undergo high power testing at NRL in the near future. D. Yu from DULY presented a design for a 17-GHz power extraction device and output coupler to be test at CLIC in October 2002. This device uses a dielectric liner inserted into a cylindrical wall to extract the power from the beam and metal output coupler to deliver the extracted power to a second beam.

Planar Dielectric Structures

As the move towards higher operating frequencies continues, interest in planar dielectric structures [5] continues to grow. Planar structures have two central advantages over cylindrical dielectric structures: an easy method for tuning by varying the gap, and a natural suppression of the transverse wakefields [6] for highly asymmetric "flat" beams. The main difficulty with making a real accelerator based on this technology is that the mechanical tolerances are tight, beam loading is severe, and very small transverse beams are needed.

Yoder from UCLA proposed a planar dielectric accelerating structure driven by 340-μm laser light. The choice of laser light is motivated by the need to keep the structure size macroscopic. He estimates that 100's of MW of 340-μm light can be generated by combining the 10.6 μm and 10.3 μm lines from the Neptune TW CO_2 laser in a non-collinear, frequency mixing isotropic gallium arsenide crystal. It is predicted that acceleration gradients of ~30 MV/m can be achieved with 50 MW of 340-μm laser power leading to an energy gain of a few MeV.

Photonic Band Gap

The photonic band gap (PBG) structure was first proposed as an accelerator in AAC 1992 [7]. It consists of a periodic array of posts, either metal or dielectric, sandwiched between two conducting planes, either normal or superconducting, in which the center post is removed. The absence of the center post causes a defect that allows the accelerating mode to become trapped while letting the HOMs propagate away, thus providing excellent damping of long range transverse wakefields. Like most of the advanced accelerating structures, the main issue for these devices is the need to be experimentally demonstrated.

Hollow plasma channels are known to have attractive accelerating properties including transverse confinement of the accelerating field, support of luminous modes with phase velocity $\leq c$ mode, and negative group velocity. G. Shvets from IIT and FNAL presented designs for two structures that mimic a hollow plasma channel with solid structures using a photonic approach. In the first method a 3D array of thin bare wires are formed into a mesh that mimics a plasma channel in the microwave band. In the second case, a plasma channel can be mimicked in the near IR band by using a CO_2 laser to drive a SiC (ε = -1.2 at 10.6 μm) photonic crystal. As with other PBG accelerators, the photonic band structure of both devices confines the accelerating mode while letting other modes propagate away from the channel. E. Smirnova from MIT presented cold test measurements and numerical simulations of a copper PBG resonator operating at 11.4 GHz in a TM_{01} mode. A user-written computer code was used to study the band gaps of the array while SUPERFISH and HFSS were used to study the array with the defect, i.e., the PBG cavity. Critical coupling into the PBG structure was achieved and a comparison between cold test measurements and simulation showed good agreement. M. Shapiro from MIT presented designs for two dielectric (Al_2O_3) PBG structures. The first device is a fundamental mode accelerator so only the TM_{01} is confined, while the second device is a higher order mode accelerator so the TM_{02} mode is confined. In both devices, simulations show the non-accelerating modes were found to be suppressed. D. Yu from DULY presented a design for a 7-defect cavity. In this device, 6 beams can be sent through the outer holes and power can be coupled out through the center hole.

Wakefield Powered Exotic Structures

Structure wakefield accelerators [8] continue to be actively investigated due to their potential for supporting high gradient electric fields and due to the lack of high peak power sources above *X*-band. A structure wakefield accelerator uses a structure (as opposed to a plasma) to extract power from a low voltage (energy), high current drive beam and transfers it to a high voltage, low current main beam. One additional advantage that a wakefield accelerator has over a conventional accelerator is that there is no RF distribution system since power is carried with the drive beam. Proof-of-principle experiments have been demonstrated for some of these techniques and it now remains to test these concepts out at full power where high accelerating gradients can be obtained.

Dielectric Rod and Vacuum Tube Discontinuity

S. Banna from Technion – Israel Institute of Technology presented the results of a set of wakefield calculations and associated wakefield effects (e.g., transverse kick) for three different geometries. The calculations were done for an electron bunch moving parallel to a dielectric cylinder, a line charge moving parallel to a dielectric cylinder, and an electron beam traveling through a geometric discontinuity.

Planar Dielectric

Previous calculations performed by the ANL group for planar dielectric structures showed that the monopole wakefield can be decomposed into the orthogonal set of symmetric LSE and LSM modes. Extending on this earlier work, C. Jing from ANL derived analytic expressions for the dipole wakefield, which are seen to be a linear combination of symmetric and asymmetric LSE and LSM modes. Instead of using the usual Green's function approach of previous authors, the beam coupling to this mode was calculated by computing the cavity parameter, R/Q. This computationally simple method has been benchmarked against MAFIA and found to be in excellent agreement. Using a Green's function approach, similar expressions derived by S. Y. Park were presented by J. Hirshfield of Yale/Omega-P. In addition to deriving expressions for the wakefields, the numerical results showed that the horizontal transverse force is defocusing at certain distances behind the drive bunch leading to instability. T. Marshall from Columbia presented numerical KARAT results that showed one can excite an accelerating wakefield of ~600 MV/m in a planar dielectric structure by using a pulse train of $10 \times Q = 1$ pC bunches, transverse profile of 10 μm × 150 μm, and bunch length of 3.3 fsec. He proposes to generate this bunch train from a 500 MeV LACARA "chopper" by passing the output beam from LACARA through a collimating mask.

FAST-WAVE ACCELERATORS

Two basic types of fast-wave accelerators were primarily discussed at the workshop: inverse free electron lasers (IFEL) [9, 10] and cyclotrons [11]. Technically speaking, both types are so-called "vacuum accelerators" and use a magnetic field to enable phase matching with the electromagnetic field. While IFELs may not have as high acceleration gradients as some other schemes, they offer many experimental advantages, which allow them to be used as true "work horses" for laser acceleration research and other applications. Examples of these applications include demonstration of staging between two laser accelerators and providing the microbunches for injection into other laser accelerator systems.

Cyclotrons also provide certain experimental advantages that make them attractive as drivers for electrons and even protons. A noteworthy development in this area is the Laser Cyclotron Auto-Resonance Accelerator (LACARA), which is not driven by RF energy, but instead uses a circularly polarized laser beam to stay synchronized with the electrons spiraling through the magnetic field.

This section briefly gives highlights of the papers presented in these two technical areas.

IFEL Acceleration

W. Kimura, STI Optronics, gave an update on the second phase of the STELLA-II experiment located at the BNL Accelerator Test Facility (ATF). STELLA-II builds upon the success of the Staged Electron Laser Acceleration (STELLA) experiment where staging between two IFELs was first demonstrated [12]. The primary goal of STELLA-II is to demonstrate staged monoenergetic laser acceleration in which the microbunches are trapped and maintain a narrow energy spread as they are accelerated in the second IFEL. To accomplish this, STELLA-II will use an 8% gap-tapered [13] undulator for the second IFEL and a single laser beam to drive both IFELs. A chicane between the IFEL undulators will serve to create the microbunches at the entrance to the second IFEL and to control the phase of the microbunches with respect to the laser field in the second IFEL.

The first fully-integrated experiments have begun. An energy gain of >13% was observed, which the authors believe is the highest gain seen from an IFEL to date. Nonetheless, the laser intensity appears lower than needed in the system. The ATF will be upgrading the CO_2 laser in the autumn of 2002. This should increase the laser peak power by ~100 times and will allow the STELLA-II experiment to achieve the required laser intensity needed to drive the IFELs.

P. Musumeci, UCLA, presented an update on efforts to test a very high gain (2.8×) IFEL at the UCLA Neptune Laboratory using its terawatt-class CO_2 laser. A key part of this experiment is the undulator, which is a permanent magnet device (5 m long) with constant gap (12 mm) and period tapering [13]. The magnetic wavelength will vary from 1.5 cm to 5.0 cm and the magnetic field will vary from 0.12 T to 0.6 T. Thus, this device will have one of the highest tapers and highest gradients ever tested in an IFEL. Another noteworthy feature of the undulator is that the magnetic field is designed to flip in the middle of the undulator to compensate for the Guoy phase shift [14], which occurs when the laser beam passes through its focus in the center of the undulator.

They predict for a 14.5 MeV input *e*-beam, that the output beam will be 55 MeV when driven by 400 GW from the Neptune CO_2 laser with a Rayleigh range of 3.6 cm. During this process, 3-fs electron pulses should be formed, which could be used as a source of microbunches for other experiments. The undulator is currently being built. First experiments are anticipated in April 2003.

X. Wang, BNL, pointed out that attosecond electron bunches would have many usages, such as probing atomic transitions and dynamics, and as injectors to laser accelerators and short-pulse *x*-ray generators. As such, he noted that the BNL ATF has the equipment and experience to generate attosecond bunches. In his proposed scheme the existing undulators at the facility, such as the STELLA permanent magnet undulators, would be driven using the fundamental frequency and 3rd harmonic from the ATF CO_2 laser, i.e., two laser beams at different wavelengths.

Two basic approaches are possible. 1) Drive a single IFEL with the fundamental and 3rd harmonic. This is predicted to yield tight microbunches, e.g., 1°, but with a sacrifice of efficiency. Or, 2) drive one IFEL with the fundamental and a second IFEL with the 3rd harmonic. This is 5 times more efficient than the first approach, but creates less tight microbunches, e.g., 5°. A critical issue, which still needs to be investigated, is how to generate sufficient power in the 3rd harmonic from the ATF CO_2 laser.

Cyclotron Acceleration

S. Shchelkunov, Columbia University, described the Laser Cyclotron Auto-Resonance Accelerator (LACARA) experiment currently being prepared for installation at the BNL ATF. The main component of the experiment is a superconducting coil that will generate a 6-T solenoidal field through which the ATF 50 MeV *e*-beam will travel. The device will be driven by 0.8 TW from the ATF CO_2 laser whose output beam has been converted to circular polarization. As mentioned, the electrons gain energy through a nearly gyroresonant interaction with the laser beam.

For an interaction length of <2 m, they predict an energy gain of 50 MeV, corresponding to doubling the energy. Thus, one advantage of this scheme is it can double the energy in a single stage. Other advantages include the ability to use a Gaussian-shaped laser beam.

Since the electrons spiral through the solenoidal field, the output *e*-beam will be annular in shape. Nevertheless, this scheme may also provide a means for creating femtosecond electron bunches by using a slit positioned at the end of the device to allow passage of a portion of the electrons in the electron pulse [15]. Plans are to install the LACARA hardware at the ATF later in 2002.

A possible alternative method for accelerating protons was introduced by J. Hirshfield, Yale University/Omega-P. The strategy to make this approach attractive is to keep the design relatively simple, have the device operate at room temperature, and use conventional RF sources for high efficiency. He gave an example configuration consisting of 8 cylindrical TE_{111}-mode cavities in series within an 8.1-T axial magnetic field. To maintain phase matching as the protons gain energy passing through the device, the cavity diameters and lengths increase with each subsequent cavity and the cavity frequency drops.

If the input proton beam is 122 mA and 1 MeV, then using a total RF input power of 174 MW, the total energy gain is 960 MeV. This corresponds to an average gradient of 40 MeV/m and a 67% efficiency. Note the output proton beam spirals and is annular in shape integrated over time. Potential applications for this 1-GeV proton beam include being a driver for a high-power neutron spallation source used for transmutation of nuclear waste.

JOINT SESSIONS

During the Workshop, two joint sessions were held with other Working Groups (WG). The first was with the MM-Wave WG, where papers dealing with more conventional RF-driven systems, including RF breakdown, were presented. The second was with the High Energy Density Physics & Exotic Acceleration Schemes WG. These papers covered the area of vacuum laser acceleration (VLA) without the use of magnetic fields and new applications. For more details on these joint sessions, we refer the reader to the summary reports in these Proceedings of these other Working Groups.

CONCLUSIONS

The technical areas covered by this WG all showed steady progress towards addressing crucial issues. There were also several noteworthy accomplishments, such the first high power tests of a DLA and over 13% energy gain in an IFEL. These represent tantalizing previews of exciting results that we can expect to see in the near future.

The WG presentations also demonstrated a healthy in flux of new ideas and new applications, and plans and proposals to improve existing approaches. Clearly, there is still a strong effort to push the capabilities of these technologies, for example, super-tapered undulators for IFELs. On the other hand, what are still missing are definitive experimental demonstrations of some of these ideas. A good example is PBG structures. It is hoped the continued efforts in these areas will change that situation soon.

Thus, by the next Advanced Accelerator Concepts Workshop we hope to see the first demonstration of a number of devices and experiments including full operation of a high-power DLA, monoenergetic acceleration by staged laser accelerators, the LACARA device, the UCLA high-gain IFEL, and perhaps a PBG device.

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